



# Finding the most suitable existing hydropower reservoirs for the development of pumped-storage schemes: An integrated approach



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## ABSTRACT

This study aims to evaluate existing hydropower reservoirs for the development of pumped-storage schemes by using multi-criteria scoring technique. This method enables a screening of existing hydropower reservoirs, in order to assess and rank potential sites for pumped-storage development. This analysis is based on the documented evidence, measured data, and site surveys. The site assessments are categorized in 6 criteria namely geometrical conditions (maximum head, head to water way length ratio, distance to grid connection), geological conditions, environmental, and social conditions. In the context of the study, 7 existing hydropower reservoirs in Turkey, each with a catchment area of more than 50 km<sup>2</sup>, are evaluated in order to be utilized as the lower reservoirs of pumped-storage facilities. The overall score of each candidate site is obtained and, their performance is compared. The results indicate that Turkey have suitable existing hydropower reservoirs for the development of pumped-storage facilities. However, the country lacks from legal and market framework for the establishment of pumped-storage power plants.

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## 1. Introduction

Pumped-storage power plant (PSPP) is a mature, large-scale, quick response, and one of the most economic storage technologies that can balance the penetration of highly variable renewable energy sources such as wind and solar [1,2]. Among the electricity storage technologies, PSPP constitute by far the most proven

technology which accounts for 99% of worldwide storage capacity of 127 GW by 2010 [3]. Compressed air storage technology, sodium–sulfur and lead–acid batteries only account for the 1% of the total installed capacity and they have relatively less life times and high lifecycle costs (Table 1). In addition, pumped-storage units can meet the peak electricity demand regardless of seasonal changes.

As a result of these benefits mentioned-above and others, many countries and companies are developing new pumped-storage facilities or upgrading their existing plants [5,6,7]. In this respect,

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several researchers have investigated the suitable sites for pumped-storage developments in their countries such as Germany [8], Greece [9], France [10], Lebanon [11], Sri Lanka [12] and Uruguay [13]. The common characteristic of those studies is that the topographic maps are used as the main data source to identify and evaluate potential sites for pumped-storage development. International Energy Agency (IEA) [14] analysis shows that existing installed turbine capacity in pumped-storage projects worldwide reached about 140 GW at the end of 2011, up from 98 GW in 2005 and IEA [14] estimates that pumped-storage capacity will increase

**Table 1**

Comparison of different bulk electricity storage technologies.

Data source: International Renewable Energy Agency (IRENA) [4]

Storage type	Life time (years)	Unit investment cost (USD/kW)	Lifecycle cost (USD/kWh <sub>life</sub> )
Pumped-storage	> 25	1000–4000	0.05–0.15
Compressed air energy storage	> 20	800–1000	0.10–0.20
Sodium–sulfur batteries	15	1000–2000	0.05–0.15
Lead–acid batteries	3–10	300–800	0.25–0.35

**Table 2**

The status of PSPPs in some European countries by 2011.

Data source: Gutierrez and Arantegui [15]

Country	Installed capacity of PSPPs (MW)	Net electricity generation from PSPPs (GWh)	Electricity generation from solar and wind (GWh)
Austria	3365	3504	2108
Czech Republic	1147	701	2564
France	6985	5074	14,285
Germany	6777	6099	68,223
Italy	7544	2539	20,443
Poland	1406	422	3205
Portugal	1029	564	9379
Spain	5260	2275	49,959
Norway	1326	406	895
Switzerland	1817	1746	120
UK	2744	2895	15,749

by a factor of 3–5 by 2050. In the beginning of 2013, the 350 PSPPs have been in operation worldwide with a total installed capacity of 152 GW; whereas 190 of them have been in operation in Europe with a total installed capacity of 51 GW [3]. Many European countries are constructing and upgrading PSPPs to deal with the growth of intermittent renewable energy sources [15]. By 2011, 170 PSPPs with a total installed capacity of 45 GW were in operation in Europe and more than half of the installed pumped-storage capacity is concentrated in four countries: Italy, Germany, France and Spain (Table 2). Zuber [16] reported that by 2020 most of the large-scale PSPPs will be developed in European countries that have favorable topographical conditions such as: Austria, Portugal, Spain, and Switzerland. For instance, in Switzerland despite the several environmental constraints, a number of large-scale projects have been under construction [17]. Those projects were mostly planned underground and they benefit from existing reservoirs in order to mitigate the environmental impacts and increase the social acceptance of the projects. Moreover, Nieto [18] emphasized the importance of the collaboration between hydro-power and environmental engineering teams for optimizing the three new PSPPs in North-Western Spain. Similarly, all those projects will benefit from existing dams and reservoirs and, almost all of the facilities will be underground reducing the requirements and scope for the Environmental Impact Assessment studies. Additionally, Fink [19] pointed out the key role of the environmental and legal issues in the permitting procedure of a large-scale pumped-storage plant in Germany.

A pumped-storage power plant involves pumping water from a lower reservoir to an upper reservoir when electricity supply exceeds demand or electricity has a lower price. Water is released from the upper reservoir to the lower reservoir through the turbine to generate electricity when demand exceeds instantaneous electricity generation or electricity has a higher price (Fig. 1). The installed capacity  $P$  (kW) of a pumped-storage plant is calculated from

$$P = \rho \times g \times Q \times (H - \Delta H) \times \eta \quad (1)$$

where  $\rho$  is the density ( $\text{kg/m}^3$ ) of water,  $g$  is the acceleration due to gravity ( $\text{m/s}^2$ ),  $Q$  ( $\text{m}^3/\text{s}$ ) is the discharge,  $H$  is the head (m),  $\Delta H$  (m) is the hydraulic head loss, and  $\eta$  is the sum of the turbine and generator efficiency.

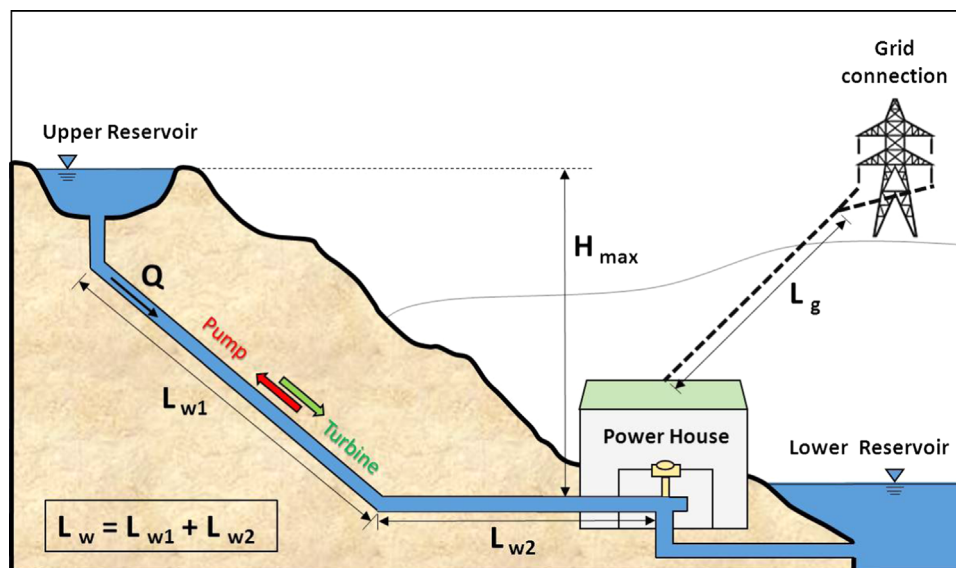
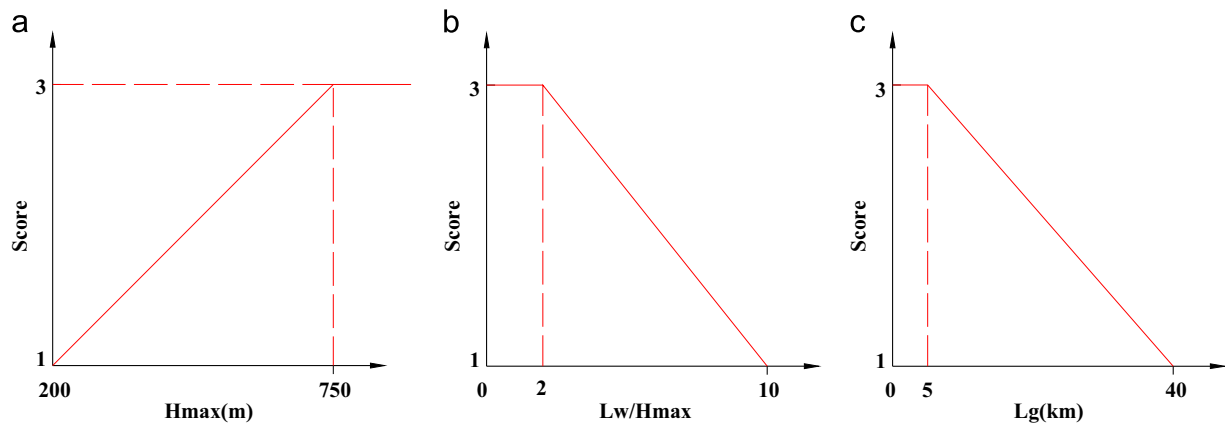


Fig. 1. Schematic drawing of a pumped-storage power plant.

**Table 3**  
Scoring criteria for geologic and environmental conditions.

Score	Parameter		
	Geological conditions	Impact on natural environment	Impact on social environment
1	High risk (exclude)	Significant negative impacts (exclude)	Significant negative impacts
2	Medium risk	Can be mitigated	Can be mitigated
3	Low risk	No significant negative impacts	No significant negative impacts



**Fig. 2.** Scoring functions for geometric parameters.  $H_{max}$ : maximum gross head (m),  $L_w$ : length of waterway connecting two reservoirs (m),  $L_g$ : grid connection distance (km). A score of 1 denotes the lowest level of suitability while a score of 3 denotes the highest.

Utilizing existing hydropower dam reservoirs for PSPP development is expected to be cost-efficient and to have low environmental impacts since there are already electricity and transportation infrastructure in place and there is no need to build lower reservoir [20]. Fitzgerald et al. [21] developed a Geographic Information Systems (GIS) based model to identify the most suitable dam reservoirs for pumped-storage development, but the authors did not take into account the site geological conditions and grid connection distance which are crucial factors for the feasibility of a hydropower project [22]. For example, the costs of the Ingula Pumped-Storage Plant in South Africa have been tripled since the planning phase mainly due to challenging site conditions [3].

Catrinu et al. [23] noted that the electric transmission lines and market conditions are the crucial factors for PSPP investments. Turgeon et al. [24] and Ert et al. [25] emphasized that site geology is one of the most important aspects for those kinds of projects mainly due to the underground facilities such as tunnels and caverns. For example, a potential site with favorable characteristics (e.g. high head and high storage capacity) but which is located far from the electrical grid infrastructure and has a poor geology will not be suitable because of the significant cost generated [10]. The aim of this study is to find most suitable existing hydropower reservoirs for pumped-storage development by using a multi-criteria scoring technique based on an integrated approach. The potential dam reservoirs in Turkey are assessed considering the site geometrical, geological, and environmental characteristics.

## 2. Methodology

In the proposed tool, a multi-criteria scoring method is used to find most favorable upper reservoirs at existing hydropower dams to develop pumped-storage schemes. An important component of the proposed methodology includes converting site characteristics into a common scale, and these scales express preferences for one site over another [26]. Suggested scales in the proposed

methodology range from 1 to 3, with 1 being the least preferable and 3 being the most preferable. The scores are assigned based on measured data and documented evidence (Table 3). Then, the Site Suitability Factor (SSF) is calculated by taking the arithmetic mean of the overall scores and a 3-grade evaluation system is established as follows:  $SSF < 2$  not suitable,  $2 \leq SSF < 2.5$  suitable, and  $SSF \geq 2.5$  most suitable. The main criteria used to evaluate potential sites are: site geology, maximum head, head to water way length ratio, distance to grid connection, impact on the natural environment, and impact on the social environment. All those criteria play an important role on the economic viability of the project, and they can directly affect the project performance such as cost and schedule overruns. The geometric criteria are presented as follows by defining a minimum requirement for each parameter: maximum head  $\geq 200$  m, maximum ratio of head to distance between reservoirs  $\leq 10$ , and maximum grid connection distance  $\leq 40$  km. Linear functions are defined for the scoring of geometrical criteria. Moreover, a threshold value is defined for the criteria of geological conditions and impact on natural environment (Table 3). If one of those parameters is assigned with a score of 1, the candidate site is excluded from the assessment. So candidate sites need to meet the minimum geometrical requirements and lie outside of environmentally protected areas. Detailed information for the selected criteria is given below.

### 2.1. Site geology

A successful pumped storage project is dependent on topographic and suitable site geologic conditions which permit proper sizing and better arrangement of the principal features [27]. Geological criteria to be considered in the study are distance from active faults, large-scale fault and fractured zones, large-scale landslide area, and existence of permeable bedrock (i.e. limestone cavities) surrounding the upper reservoir [28]. If the permeability of the rock is too high or the rock contains karstic cavities, surrounding water could possibly leak into the lower reservoir. In order to avoid delays and extra costs during the construction

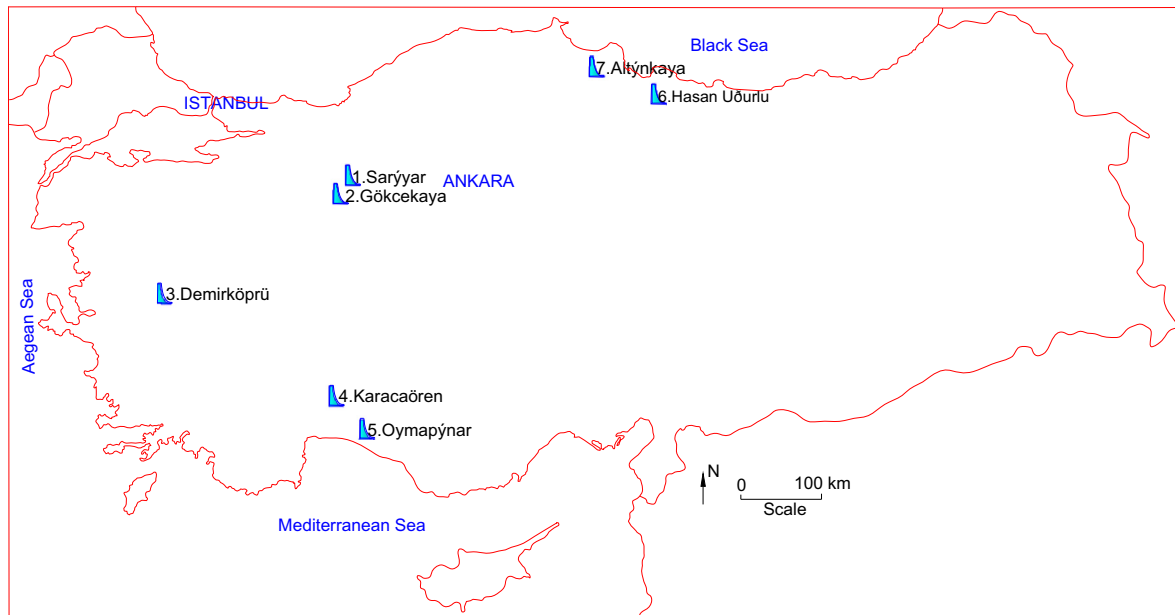


Fig. 3. Map of Turkey showing the locations of the selected hydropower reservoirs in Turkey.

phase, favorable geological conditions at the potential site are desirable.

## 2.2. Impact on natural environment

The scheme possible impacts on the natural environment through habitat destruction and biodiversity loss are taken into account. Sensitivity regarding environmental aspects must be ensured, so that critical habitats, threatened species, and spawning areas can be protected.

## 2.3. Impact on social environment

The social environment criteria that are taken into account are: number of directly affected houses (resettlement), relocation, and area of the lost land that local communities use for their live hood (i.e. agricultural land).

## 2.4. Maximum head

It is a difference in height between proposed upper basin and lower basin. With a small rated head, either the rated power will be small or the investment high because of the larger turbines and basins. The higher heads will decrease the construction and equipment costs [29]. In this respect, higher heads represent preferable site conditions and they have higher scores (Fig. 2a).

## 2.5. Head to water way length ratio

In addition to operating head, the other key parameter is the length of waterway connecting the upper and lower reservoirs [29]. The shorter length becomes the better the project will eventually be that may result in low cost and hydraulic losses. Also, the construction challenges and excavation costs are expected to decrease as the water way length decreases. The ratio of length to head falls between 2 and 10 for most pumped storage projects and small values correspond to a higher score (Fig. 2b).

Table 4

Characteristics of selected hydropower reservoirs in Turkey.

Data source: TEIAS [32]

No.	Dam name	River	Province	Start of operation	Reservoir elevation range (m)	Active storage capacity (H m <sup>3</sup> )
1	Sarıyar	Sakarya	Ankara	1956	460–475	1698
2	Gökcekaya	Sakarya	Eskişehir	1972	377–389	953
3	Demirköprü	Gediz	Manisa	1960	222–244	1022
4	Karacaören	Aksu	Burdur	1989	245–270	1234
5	Oymapınar	Manavgat	Antalya	1984	166–184	297
6	Hasan Uğurlu	Yeşilırmak	Samsun	1981	150–190	1018
7	Altınkaya	Kızılırmak	Samsun	1988	160–190	5763

## 2.6. Distance to grid connection

Construction of a new transmission line is costly and could be complicate since it involves obtaining appropriate permits and may also require land acquisition [24]. Therefore, the closer the PSPP is located the existing transmission lines, the lower costs of integration to the grid will be. So, the distance to the grid connection should be short, and the score is inversely proportional with the grid connection distance (Fig. 2c).

## 3. Application of the proposed methodology to hydropower reservoirs in Turkey

Turkey is situated through a mountainous topography (average altitude=1132 m) and own an annual average runoff value of 186 billion m<sup>3</sup> which favor ideal locations for hydropower development [30]. By September 2013, 69 storage type and 365 run-of-river type hydropower plants have been in operation in the country with a total installed capacity of 15.5 GW and 5.6 GW, respectively [31]. Currently there is no pumped-storage power plant is in operation. However, the electric market conditions and rapid development of wind energy in the country indicate a need

**Table 5**

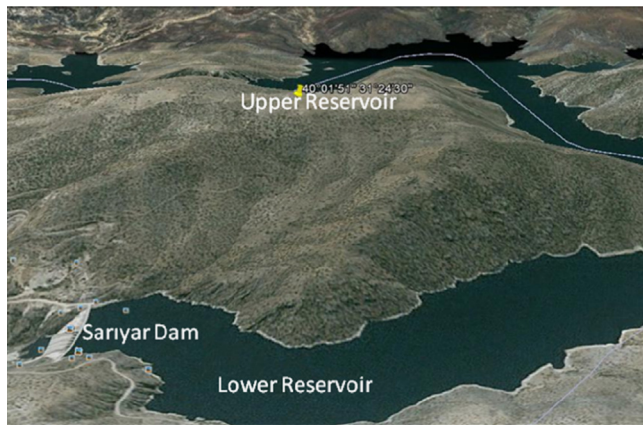
Characteristics of the potential upper reservoirs for PHES development at existing hydropower reservoirs in Turkey.  
Data sources: JICA [28], for Sarıyar Dam, Steyer and Reuter [34]

Dam name	Criteriaion		$H_{max}$ (m)	$L_w$ (m)	$L_w/H_{max}$	Upper reservoir active storage capacity ( $H\ m^3$ )	$L_g$ (km)	Remarks
	Upper reservoir, Latitude (N), Longitude (E)							
1 Sarıyar	40°01'51" 31°24'30"		310	800	2.58	6.0	25	Excavation is needed to build upper reservoir.
2 Gökçekaya	40°03'51" 30°59'31"		422	3649	8.65	8.4	20	No house will be directly affected, 16 ha agricultural land will be lost. Possibility of landslides surrounding the site.
3 Demirkoprü	38°39'01" 28°19'36"		213	1435	6.74	1.9	5	The site is located in the vicinity of an active fault.
4 Karacaoren I	37°24'49" 30°55'34"		618	4824	7.81	5.7	40	The site is located in the limestone zone. Weathering near the lower reservoir is identified.
5 Oymapınar	36°55'43" 31°34'46"		744	2546	3.42	4.7	20	Underflows from limestone cave (Dumanlı spring) submerged in the Oymapınar Dam reservoir.
6 Hasan Uğurlu	40°51'47" 36°29' 48"		570	2300	4.04	2.2	30	Upper reservoir is located in a dense forest land. The project is expected to have high environmental and social impact.
7 Altınkaya	41°23'48" 35°35'30"		650	5302	8.16	5.4	10	3 Houses will be directly affected, 110 ha agricultural land will be lost, several graves will be relocated. Possibility of landslides surrounding the site.

**Table 6**

Assessment of the potential upper reservoirs for PHES development by assigning scores.

Dam name	Criterion						
	$H_{max}$ (m)	$L_w/H_{max}$	$L_g$ (km)	Geological conditions	Impact on natural environment	Impact on social environment	Site suitability factor
Sarıyar	1.40	2.86	1.79	3	3	3	SSF=2.51 Most suitable
Gökçekaya	1.81	1.34	2.05	2	3	3	SSF=2.20 Suitable
Demirkoprü	1.05	1.82	2.84	2	3	3	SSF=2.28 Suitable
Karacaoren I	2.52	1.55	1.00	2	3	2	SSF=2.01 Suitable
Oymapınar	2.98	2.65	2.05	1	3	3	Excluded
Hasan Uğurlu	2.35	2.49	1.53	2	1	1	Excluded
Altınkaya	2.64	1.46	2.58	2	3	2	SSF=2.28 Suitable



**Fig. 4.** A 3D view of Sarıyar Dam site. The candidate upper reservoir site is located on a flat mountain peak. The figure is created from Google Earth.

for pumped-storage power schemes. In the context of this study, 7 existing hydropower reservoirs are selected for the assessment (Fig. 3). The criteria for finding existing hydropower reservoirs for pumped-storage projects are as follows: the reservoir has a catchment area of more than 50 km<sup>2</sup>; the reservoir is located along mountainous topography, and it must be lie outside the culture heritage and protected areas (e.g. natural parks). The characteristics of the selected hydropower reservoirs are presented in Table 4. All reservoirs have sufficient active storage capacity [32] for potential development of large-scale PSSP where

road and electric infrastructures (all necessary infrastructures) already exist.

Characteristics of potential upper reservoir sites are given Table 5. The presented data in Table 5 are based on the site surveys that were conducted by Japan International Cooperation Agency (JICA) [28] and the topographic and geologic maps of the regions. The geometrical shapes of identified sites favor the construction of upper reservoirs. Each site has different favorable characteristics: Sarıyar reservoir has the lowest value for  $L_w/H_{max}$  ratio as 2.58, Gökçeya reservoir has the highest active storage capacity for the upper reservoir as 8.4 H m<sup>3</sup>, Demirkoprü reservoir has the shortest grid connection distance of 5 km, and Oymapınar reservoir has the highest gross head value of 744 m. However, geometric aspects are not enough to assess a site for PSSP development; the potential sites must also be evaluated in an integrated approach, taking into account the geologic and environmental conditions. For instance, in Turkey there are various types of active faults: the North Anatolian Fault is the biggest active fault, and the East Anatolian Fault is the second biggest. In this respect, Demirkoprü Hydropower Plant is located within a distance less than 10 km from the active fault, which is evident in the geologic map of the region [33].

Additionally, Turkish land is extensively covered with soluble; mainly carbonate rock formations with karst springs that significantly affect the water resources [35]. For instance, Oymapınar reservoir is fed by a kartsic spring called Dumanlı which is thought to be the largest spring in the world with a 50 m<sup>3</sup>/s mean annual discharge [36]. Dumanlı Spring is submerged in the Oymapınar reservoir which may lead high geologic risk for pumped-storage development in this



region. Moreover, Hasan Uğurlu dam reservoir is surrounded by an intense forest land and the region is densely occupied; therefore a project development in the area is expected to have significant negative environmental and social impacts.

Based on gathered data, the suitability of each candidate site is evaluated by assigning scores in an objective manner and the results are presented in Table 6. Two candidate sites namely Oymapınar and Hasan Uğurlu are excluded based on geological and environmental criteria, respectively (Table 6). The results reveal that four sites (Gökçekaya, Demirkopru, Karacaoren I, and Altinkaya) are found to be suitable for pumped-storage installations. The Sarıyar Reservoir turns out to be the most preferable (top-scored) site for the implementation of a pumped-storage plant due to region's favorable site conditions particularly based on geologic and environmental criteria. Fig. 4 shows the 3D view of Sarıyar Reservoir and the location of the potential upper reservoir which is situated on a flat mountain peak. The Sarıyar reservoir forms a semicircle on a length of 6 km upstream the dam location. The maximum operating level of the reservoir is at the elevation of 475 m and the active storage volume is 1.7 billion m<sup>3</sup>. The possible head of fall between lower reservoir and hill top is 310 m and the horizontal distance is 800 m [34].

#### 4. Conclusions

In Turkey the current electricity market conditions, peak electricity prices are almost three times higher than the electricity prices during the night period, the rapid developments in intermittent renewable energy sources, and the plans for to build-up two nuclear plants in the near future, indicate the necessity of the construction of pumped-storage power plants (PSPPs) in the country. In this context, the existing hydropower reservoirs in Turkey are assessed in order to develop PSPPs by applying a multi-criteria scoring technique in an integrated approach. Existing hydropower reservoirs are chosen because of their expected much lower environmental impact than, for example, closing a valley with a dam. The methodology involves a detailed environmental and social impact assessment by using 1:25,000-scale topographic maps and measurable relevant parameters supported with field studies. The potential sites geologic risks (active faults, karstic cavities, landslides), which were ignored in previous studies, are also evaluated in the proposed methodology.

The candidate hydropower reservoirs are classified as not suitable, suitable, and most suitable based on their Site Suitability Factor (SSF) values. The results reveal that Turkey has suitable hydropower dams and reservoirs for converting into pumped-storage facilities. The most favorable hydropower reservoirs for PSPP development are found as Sarıyar, Demirkopru, Altinkaya, and Gökçekaya. All of those hydropower reservoirs have active storage capacities larger than 1 billion m<sup>3</sup>. Currently the country lacks legal and market framework for the establishment of pumped-storage power plants. In coming years, framework conditions should be created in the country to allow electric storage infrastructure to be developed.

By applying the proposed Site Suitability Factor, the responsible government agencies and project developers can assign priority ranks on the candidate sites and they can make a comparison between the alternatives. Additionally, project developers and investors can gain competitive advantage in the field of pumped-storage deployment and they can develop a strategy in project planning stage to cope with the project risks and complex permitting procedure. For now, the investigated sites cover Turkish hydropower reservoirs. However, the developed tool can be applied to other hydropower reservoirs worldwide by adjusting the relevant parameters. The main advantages of the proposed methodology are its ease of use and simplicity.

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